

Acoustic Agglomeration of Power Plant Fly Ash for
Environmental and Hot Gas Clean-Up

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INTRODUCTION AND STATEMENT OF PROBLEM

Current techniques to remove particulates in coal fired power plant flues are based on electrostatic precipitators, bag houses and wet scrubbers. Typical collection efficiencies of such devices and the far less efficient cyclones are shown in Figure 1. Of interest is the fact that below $1\text{ }\mu\text{m}$ the efficiencies drop off rather precipitously. Work presented by Davies [1], Figure 2, has shown that the human lower pulmonary system is unfortunately most efficient in absorbing and retaining particles in the $1\text{ }\mu\text{m}$ range. These particles are the primary cause of such respiratory ailments as bronchitis, emphysema and lung cancer.

Observations indicate that currently, approximately 50% of the particles suspended in an urban atmosphere are smaller than $1\text{ }\mu\text{m}$ [2]. This fact appears to be in part the result of the low efficiency of particle collection devices for the removal of these small particles. Therefore, legislation has been under consideration at the Federal level which will include recognition of particle size rather than just mass removal which is the sole criterion in current Federal legislation. California and Maryland have already legislation in effect which, as a result of a "no visible emission" statement, provides some control of submicron particulates.

The agglomeration or growth of the submicron and low micron sized particles into 5 to 20 micron sized agglomerates using high intensity acoustic fields for subsequent efficient removal by conventional particle removal devices, such as those mentioned earlier, is one of the most attractive alternatives and the subject of this paper. Acoustic agglomerators would, therefore, be aerosol conditioning devices in clean-up trains consisting for example, of a first stage of cyclones to remove the largest particles followed by an acoustic agglomeration device with the resulting enlarged particles being removed by any one of the conventional cleaning devices.

Accelerated agglomeration of particles in sound fields is not a new idea. William Ostwald first suggested the use of acoustic agglomeration to collect liquid particles as early as 1866. Notable among the early studies is the work of Smoluchowski [3], in Germany in 1915; Andrade [4]; Brandt, Freund and Hiedeman in Germany [5,6] in 1936; St. Clair [7] in the United States between 1938 and 1950; Stokes [8] in the United States in 1950. Of much interest is the work of Neumann, Danser and Soderberg and Fowle [9-14], at Ultrasonic Corporation in Cambridge, Massachusetts during the early 1950's, who developed commercially available acoustic coagulators for such diverse applications as cement plants, open hearth gas dust removal, calcinated soda removal, molybdenum disulfate, ammonium chloride, carbon black and other dust as well as liquid aerosol agglomeration. The most thorough and often quoted work was done by Mednikov [15], and other in Russia in the 1960's. More recent work by Volk [16,17] in the United States at Penn State University has shown significant agglomeration of carbon black, white lead, kaolin clay and fly ash dusts at rather modest acoustic levels, between 100 and 120 dB with frequencies in the 1000 to 6000 Hz range, representative dust loadings between 0.5 to 2 gm/m^3 , and exposure times varying from 10 to 40 seconds. Scott [18], in Canada performed very interesting and important studies on the effect of nonlinear acoustic effects on agglomeration. Shaw [19 - 20], and his associates at the State University of New York at Buffalo have performed research of both a theoretical and experimental nature on acoustic agglomeration with special emphasis on the phenomena of

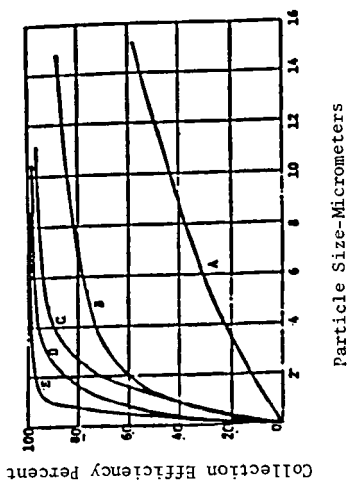


Figure 1. Collection efficiencies of several particle removal devices

A. High Throughout Cyclone
 B. High Efficiency Cyclone
 C. Dry Electrostatic Precipitator
 D. Spray Tower
 E. Scrubber

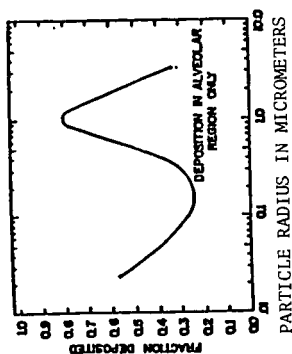


Figure 2. Absorption of particles in the human pulmonary system

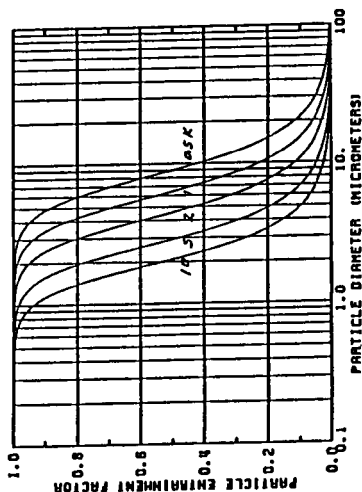


Figure 3

acoustically induced turbulence at very high levels of acoustic intensities and also the effects of acoustically induced shock waves. Research at Penn State over the last two years under the authors direction, has not been able to identify such high acoustically generated turbulence levels under similar conditions. This important subject will be discussed in the paper. On the other hand, very effective agglomeration of submicron sized particles of fly ash at flue temperatures was obtained by us with similar acoustic levels of 155-165 dB but at frequencies in the 2500 Hz range and exposure times of about 4 seconds. The details of these experiments and the theoretical foundation will also be discussed in this paper.

Recent very successful demonstrations of the high efficiencies that can be achieved with combined cycle gas turbine-steam turbine power plants using pressurized, fluidized bed coal combustion heat sources have shown that gas turbine life is severely limited because even the most efficient available hot clean-up devices cannot remove the small erosive particles from the 6 to 10 atmosphere, 1600°F gas streams. Acoustic agglomeration in conjunction with high efficiency cyclone trains appears to be the only viable means of making this promising new power plant concept feasible. We must also mention the acoustic agglomeration experiments conducted by the Braxton Corporation [22] in 1974 which did not give good results. In fact, essentially no agglomeration was experienced in this rather large scale facility. These tests which were supported by EPA, were performed at a frequency of 366 Hz and intensities of 165 dB. Redispersed cupola dust of about 4 μm mean size and fly ash of about 6 μm mean size were used as dusts. The results of our research and Dr. Shaw's work clearly show that for the type and size of dust used, frequencies on the order of 2500 Hz and 3000 Hz provide optimum agglomeration. It is, therefore, not surprising that very poor results were obtained by the Braxton experiments.

From these introductory remarks it is apparent that much work has been done on both the theoretical and the practical aspects of acoustic agglomeration.

The research results to date at Penn State University show conclusively that acoustic agglomeration of fly ash can be accomplished yet further research is required on several important acoustic and coagulation phenomena before large scale demonstration of the technical and economic viability of the process can be accomplished. The work reported has been supported by the Pittsburgh and Morgantown Energy Technology centers of the U.S. Department of Energy.

THE FUNDAMENTALS OF ACOUSTIC AGGLOMERATION OF SMALL PARTICULATES

Let us consider a polydisperse aerosol consisting of submicron and micron sized particles. The mean separation distance between particles would typically be about 100 microns. Brownian movement of the particles is caused by the collision of the thermally agitated air molecules with the particles. Also any convection currents or turbulence in the carrier gas will of course cause the particles to be partially entrained and moved in the air. If we next impose an acoustic field of acoustic pressure p , the acoustic velocity u will be given by

$$u = \frac{p}{\rho_0 c} \quad 1)$$

where ρ_0 is the air density and c is the speed of sound in the air. For a typical acoustic sound pressure level of 160 dB the acoustic velocity will be about 5 m/sec (for 150 dB the acoustic velocity will drop to 0.5 m/sec, on tenth this value). For a typical acoustic frequency of 2000 Hz a fully entrained particle might flit back and forth 2000 times a second over a distance of about 600 μm. Let us next apply Newton's second law to a spherical particle equating the particle mass times its acceleration to the Stokesian or viscous drag forces

$$\frac{d}{dt}(u_p) = (u_g - u_p) \frac{18 \mu}{\rho_p d_p^2} = (u_g - u_p) \frac{1}{\tau} \quad 2)$$

where u_p is the particle velocity, ρ_p the particle density, d_p the particle diameter u_g the gas velocity, μ the gas dynamic viscosity and τ the particle relaxation time. The particle Reynolds number for these conditions is rather low in the range 2-10. Solution of equation (2) with $u_g = U_g \sin(\omega t - \phi)$ where ω is the acoustic frequency and t is time is of the form

$$u_p = \eta_p u_g \sin(\omega t - \phi) \quad 3)$$

where η_p is the entrainment factor of the particle and ϕ is the phase angle between particle and gas motion. The factor η_p is then given by

$$\eta_p = 1/(1 + \omega^2 \tau^2)^{1/2} \quad 4)$$

Thus for $\eta_p = 1$ full entrainment occurs and for $\eta_p = 0$ no entrainment occurs meaning the particle stands still. For a particle density of 2300 kg/m^3 corresponding to fly ash dust and frequencies of 500, 1000 2000, 5000, 10,000 Hz, the entrainment factor η_p is plotted for various particle diameters in Figure 3. For each of the frequencies there is a cut particle size below which particles are almost fully entrained. For example, for the 2000 Hz case the cut particle size is about $4.5 \text{ } \mu\text{m}$. The large particles compared to the cut size are essentially still, the small particles are moving through large displacements colliding with the large particles, adhering to these particles because of the large Van der Waal forces. In a slowly convecting field we can, therefore, think of the large particles as cleaning out the small particles thereby generating empty spaces. One of the long standing unanswered questions in this field has been how the refill of these swept out volumes occurs? Every investigator in this country and abroad has assumed either explicitly or tacitly that the swept out volume would be refilled in just one cycle without giving a justification. Penn State's most recent agglomeration analytical model also is based on this premise and, as will be shown later, gives good agreement between our measurements and prediction.

We recently completed an analytical investigation of the flow field near slowly drifting spheres at Reynolds numbers from 0-10. The interaction of flow fields between two moving spherical particles of unequal size required the solution of the uncoupled Navier Stokes Equations using 5th and 6th order Runge-Kutta-Verner method and applying experimentally obtained expressions for the drag coefficient as a function of Reynolds number. Typical results are shown in Figure 6 for a 10 micron and a 1 micron particle exposed to an acoustic field of 150 dB at 2500 Hz for several acoustic cycles. The 120 micron particle remains essentially stationary and is shown at the origin of the plot. The trajectory of the central position of 9 different (one at the time) particles entering from the right side are shown with each little circle depicting the particle after each acoustic cycle. The larger the spacing between little circles along a trajectory the larger the velocity. The important conclusion to be drawn is that the flow field around the large particle causes the small particles which are vertically higher than 10 microns to assume a significant orthogonal velocity to the acoustic velocity thereby being able to refill the swept-clear volumes. Actually the particles sweep through about 250 microns during each cycle as shown in Figure 5. Our calculations show that this phenomenon explains about 85% of the refill, the rest resulting from gravitational and turbulent diffusion processes.

In a separate investigation we have determined that the agglomerates up to modest sizes are sufficiently robust to withstand the rigors of the flow through cyclones and electrostatic precipitators. The research is based on experimental

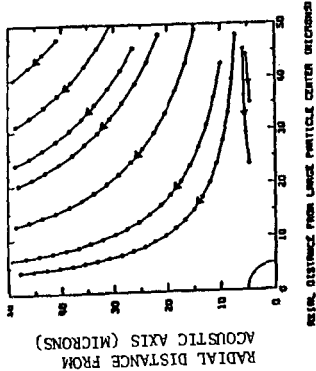


Figure 4. Hydrodynamic interaction of particles shown for several cycles

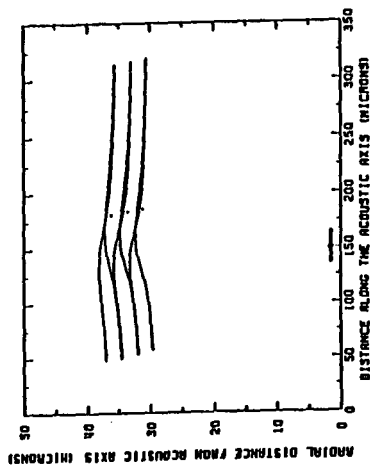


Figure 5. Hydrodynamic interaction of particles for 3 acoustic cycles. Acoustic waves of 2500 Hz frequency and 150 dB sound pressure level, particles of 1 and 10 micrometer diameter. The circles show mean positions during the acoustic cycles.

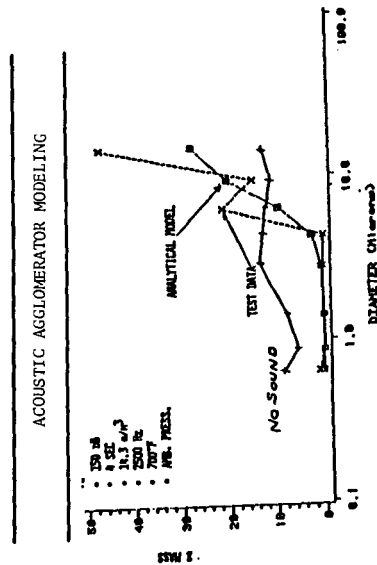


Figure 6. Results of Acoustic Agglomeration Model and Comparison with Test Data

results with inertial separation devices (impactors) and comparing the experienced shear stresses in impactors as determined from theory, with the shear stresses expected in cyclones.

A further experimental investigation has established that acoustically generated turbulence at these high acoustic intensities is not the dominant mechanism of agglomeration and that the acoustic velocities as explained earlier are the primary kinetic sources.

We have recently developed a computer code for the simulation of the agglomeration processes using these just mentioned advances in our knowledge. The principal mechanism is the orthokinetic process including also Brownian movement and several other factors. The code is in effect a simulation of the agglomeration process. The initially log normally distributed particle size distribution is divided into a number (75) of particle size ranges. As particles within ranges and particles from one range collide with particles from another range, the code moves the agglomerated particles into the range containing particles of the particular agglomerate size. The code assumes that all collisions result in agglomerations and that no break-up of agglomerates occur. Furthermore, the results of several other earlier investigations performed by us are included in the model. For example; the results of our fragility study permit us to exclude fractional agglomerate break-ups; the acoustically generated turbulence studies permit us to consider only acoustic velocity caused aerodynamic flow field; our recent results with the fluid mechanics of the flow near spheres at low Reynold's numbers permit us to assume that refill of swept out volumes occurs within just a very few oscillatory periods. A typical result is given in Figure 6 comparing experimental results from impactor measurements with our prediction. The agreement is indeed most encouraging. What is also evident from this one example is that indeed we do obtain very significant agglomeration; in fact the particles smaller than 6 microns are essentially eliminated. More on the matter later. We must point out, however, that the agreement between our idealized model and experiment is not as good for higher acoustic intensities and longer time exposures. We are continuing our research toward improving the model.

DESCRIPTION OF THE 700°F ACOUSTIC AGGLOMERATOR

We have developed and used several acoustic agglomerators over the past 11 years that we have been working in this field. We are describing here the currently operating atmospheric pressure agglomerator which permits temperatures up to 700°F, sound pressure levels from 130-165 dB, sound frequencies from 1000-4000 Hz, dust loadings from 2 gr/m³ to 30 gr/m³, flow rates from 0.4 to 4 ft/sec in the 8 foot long agglomeration section. Noise exposure times therefore range from 2 seconds to 20 seconds.

The agglomerator is shown in the partial sectional view in Figure 7 and the system is shown in Figure 8. Starting from the left we have the 600 acoustic watt siren designed and built at Penn State. Compressed air is provided by a Roots-type blower. Pressure to the siren is controlled by means of a bypass valve. We note that the siren is acoustically coupled to the 8-inch internal diameter agglomerator chamber by an exponential type acoustic coupler. The 9.25 inch long tubular section has 16 - 0.5 inch diameter exhaust holes for the siren air. The acoustically transparent barrier prevents the cold siren air from flowing into the heater section. The sheet of felted, woven and sintered stainless steel has a flow resistance of 110 MKS rays giving an acoustic transmission loss of only 4 dB. By automatically controlling the pressure drop across the barrier to about 1 inch of water, we are able to minimize cold siren air flow into the agglomeration chamber. Control is obtained by an automatically controlled damper valve in the final exhaust section of the system. We sense the pressure drop by means of a Valedyne differential pressuresensor which in turn, through appropriate electronics, controls the stepping motor activated damper valve. A sluice type gate valve is installed as noted to

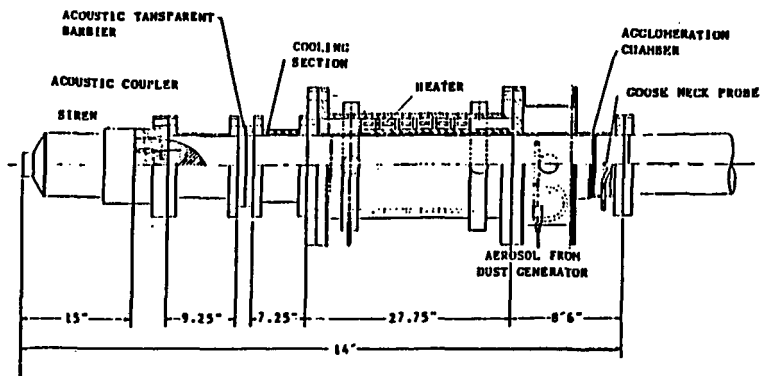


Figure 7. Moderate Temperature Acoustic Agglomerator

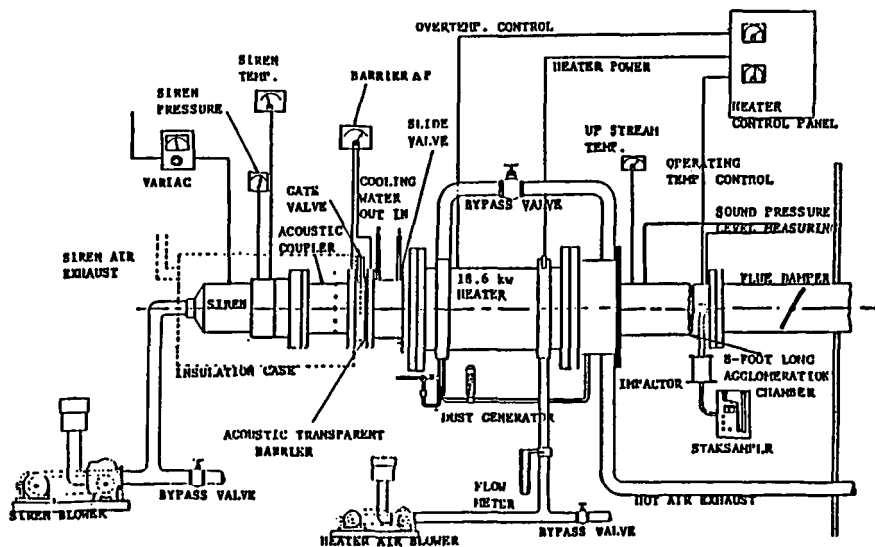


Figure 8 . Final Setup of Moderate Temperature Acoustic Agglomerator Facility

prevent hot air backflow during the many hours of heater-only time to reach the desired system temperature.

The 7.25 jacketed, water cooled section prevents heat conduction to the siren system thus protecting the wooden horn and siren from over-temperature. The heater section consists of a 14 inch schedule 40 pipe with 150 lb. flanges welded to each end. Six Chromolox Model KSEF-Koilfin electric heating elements generate 18.6 KW of heating power which is transferred to the airflow by convection. The system can be cycled at 3 Hz holding the temperature within just a few degrees. Air velocity over the heaters is 10 ft/sec. to maintain proper heating element temperatures. System schematic diagram Figure 10 shows the Roots-type blower with bypass flow control and orifice meter flow sensor providing the heating air to the system. Only about 10% to 20% of the heated air actually enters the agglomerator through 24-1/8 inch diameter angled holes. An adjustable sleeve valve controls the exposure of these holes. The excess hot air is then passed through the bypass control valve into the aerosol distribution section to heat the aerosol to the gas temperature. Finally the hot air is exhausted to the out-of-doors. The aerosol concentrate distribution system is attached to the heater flange as shown in Figure 7. Four equal length copper tubes from the aerosol manifold are connected to the four 90° spaced holes on the 8 inch diameter tube.

The aerosol generator is a simple plated standard aspirator of the type used in laboratories to obtain a vacuum source from a water supply. It is modified by removing the original vacuum line attachment and is connected to a cylindrical glass tube as the reservoir for the dust. A pulse of air traveling through the aspirator creates a short time duration low pressure which causes a controlled amount of dust from the reservoir to be sucked down the pipe line and into the agglomeration chamber. The pulsed air is produced by passing the compressed air through a solenoid valve. The time that the air is permitted to flow through the aspirator (pulse time) and the pulse frequency are controlled by a Pulse/Lapse Timer connected to the solenoid valve.

Agglomeration takes place in the 8 foot long, 8 inch schedule 40 pipe. A 1/2 inch gooseneck sampling probe is located in the end of the section. Isokinetic samples were drawn by the RAC Staksampler into an Anderson Mark III particle-sizing stack impactor which is designed for use up to 1500°F. The impactor consists of a series of plates with a number of holes arranged as shown in Figure 9. The holes are displaced on successive plates so that a gas stream, after going through the holes in a plate, impacts a surface and must make a sharp turn to enter the holes in the next plate. The impactor operates on the theory that at each stage smaller particles flow with the air stream during the sharp turn; larger particles, due to their greater inertia, will go straight the deposit on to the plate. As shown in Figure 9 each plate has holes smaller than those in the previous plate and, therefore, the velocity increases at each stage, depositing particles of given size ranges at each level. A final filter collects any particles which remain after the last plate. A glass fiber substrate with properly located cutouts is placed on each stage as the collection medium. Each substrate is weighed before and after exposure to determine the mass of particles of each size collected; and it is dehydrated before weighing to eliminate the factor of the weight of moisture. The range of particle diameters that will collect on a plate at each stage is determined by the aerosol flow rate through the impactor.

The impactors are preheated in a small furnace to the temperature of the aerosol being tested.

The piping from the upstream heater flange to the end of the 8 foot agglomeration tube is covered completely with 2 inch thick thermal insulation (calcium silicate or Epytherm) and aluminum sheeting to reduce heat loss, increase acoustic transmission loss and reduce temperature gradients in the test section.

The acoustic pressure sensors were attached to small water jacketed coolers which were screwed into the hot agglomeration chamber pipe wall to provide protection from the high temperatures.

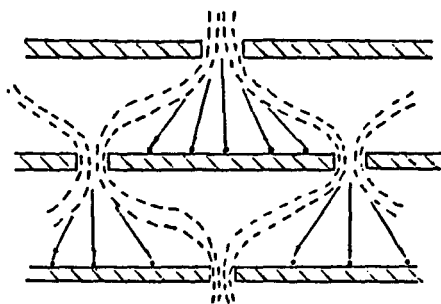


Figure 9 Schematic of Impactor Stage

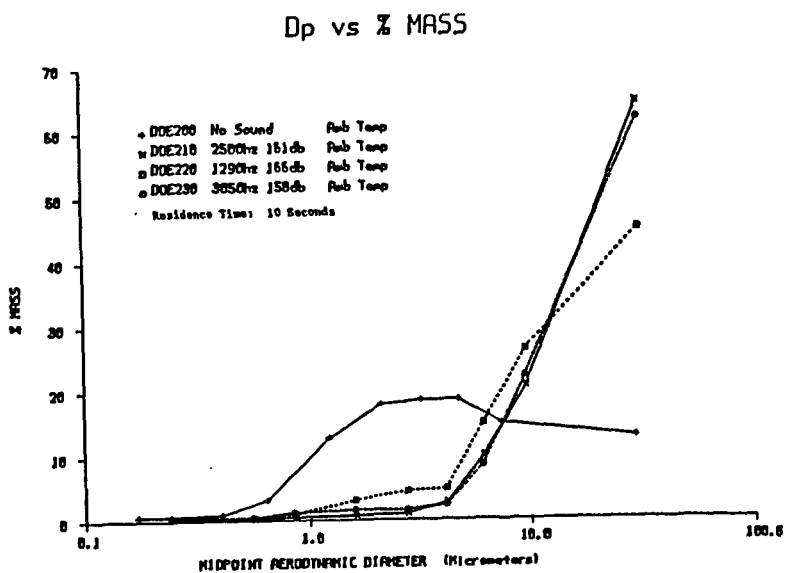


Figure 10

Because of the importance of the sound source in terms of its overall efficiency, reliability and cost, we shall describe the siren design in somewhat greater detail. Before deciding on the siren as a very promising sound source, we investigated several other potential high acoustic sound pressure sources. Hartmann Whistles (generators) provide efficiencies of about 5%. Air powered, electrically driven oscillating sleeve valve type drivers are on the market with acoustic outputs in the 2 KW to 40 KW range. Their efficiencies are in the 8% to 10% range. These latter sound sources can provide the broad band sound required in the acoustic fatigue test installations for which they were designed. Generally, they are not designed for long life applications. These sources work at considerably lower frequencies than needed for acoustic agglomeration. Another well-known high power source is the St. Clair generator which is basically a resonant cylinder vibrating in an axial mode. Kilowatt range powers in the 1 to 15 KHz range have been produced with overall efficiencies in the vicinity of 6%. Sirens have been shown to be the only sound source which promises to provide the high overall efficiencies of from 50 to 60% required for economically viable acoustic agglomerators in power plant applications. Also, properly designed sirens offer the promise of the required long life, high reliability, low operating costs and relatively low initial cost compared to other systems.

Almost all commercial sirens are used for fire and air raid warning systems. They have frequencies in the 250-500 Hz range and produce acoustic power in the 100-1000 watt range and are not very efficiency sound producers. We have, therefore, developed the technology to design high efficiency reliable sirens. Our work is built on a foundation of research at Penn State in the 1950's, some recent excellent work in Poland, Russia and in Japan. The siren used in this research develops about 600 acoustic watts in the desired frequency range giving us sound pressure levels in the 8 inch duct up to 165 dB. Almost all the energy is contained in the fundamental frequency.

Recent Experimental Results

The agglomerator has performed reliably and the results were quite repeatable. We have used a processed fly ash dust consisting primarily of Silica, Alumina and Iron Oxide particles. A typical set of results is shown in Figure 10 for a dust loading of about 2 gr/m³ and an exposure time of 10 seconds. The results show that the maximum agglomeration for this density of dust and this particular size distribution does occur near the predicted value of 2500 Hz with clearly less agglomeration at 1290 Hz. Earlier experiments with heavier white lead dust followed prediction and gave an optimum frequency of about 1500 Hz.

Space limitations do not permit to show the full range of parametric effects.

CONCLUSIONS

Our theoretical and experimental work has shown conclusively that acoustic agglomeration does result in shifting the particle size distribution from submicron sizes into the 10 micron and above size range. In order to achieve the desired 150 to 160 dB specific acoustic powers of from 0.1 to 1 watt/cm² are required for plane wave propagation and less than that for standing wave chambers.

We have reached an understanding of the fundamental processes and an ability to model the process permitting us to perform approximate trade-off studies for various clean-up train strategies involving various types of clean-up devices at different locations in the system. For example, a hot gas clean-up system consisting of a pressurized, fluidized bed coal burner producing 10 atmospheres, 1650°F gas with a loading of 10,000 parts per million by weight with a particular size distribution followed by a Stairmand cyclone, an acoustic agglomerator which is followed by a high efficiency Van Tongeren cyclone. To meet the required 25 ppmw dust loading requirement we predict exposure times of 9 seconds at 155 dB, 5 seconds at 160 dB

and 3 seconds at 165 dB. Since long exposure times mean large agglomeration chambers and high acoustic intensities require more power from the power plant cost trade off optimization studies can be performed. As a general statement, we can say that the power required to operate the acoustic agglomeration system is about 0.02 to 0.5% of the power plant output. For a 250 megawatt power plant we would need anywhere from 50 KW to 1250 KW for the acoustic agglomeration system. At 50% overall efficiency the acoustic power would range from 25 KW to 625 KW. These are very large acoustic powers when compared to the acoustic power output of a 4 engine commercial jet aircraft of about 36 KW on take-off.

We are continuing our research with U.S. Department of Energy support to further improve our understanding of several important aspects of acoustic agglomeration such as acoustic energy absorption by hot gases and large particle concentrations, nonlinear acoustic phenomena, output and efficiency, the effect of acoustic agglomeration chamber geometry on the acoustic field. We are also involved in several other applications of acoustic agglomeration for dust control.

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